Remote Imagery for Unmanned Ground Vehicles (RIUGV)

Philip A. Frederick*[a], Robert Kania[a], Bernard Theisen[a], Derek Ward[b], Ursula Benz[c], Alex Baylot[d], John Willis[e], Harold Yamauchi[e]

[a]US ARMY Tank, Automotive, Research, and Development Center and Automotive Center, 6501 E Eleven Mile Road, AMSRD-TAR-R MS 264, Warren, MI, USA 48397
[b]Lockheed Martin Missiles And Fire Control - Dallas , PO Box 650003 MS WT-52, Dallas TX, USA 75265
[c]Definiens Imaging, Trappentreu str. 1, 80 339 Munich
[d]US ARMY Engineer Research and Development Center, 3909 Halls Ferry Road, CEERD-GM-M, Vicksburg, MS, USA 39180
[e]TRADOC Analysis Center, USA TRAC-MTRY P.O. Box 8695, ATRC-RDM, Monterey, CA USA 93943

ABSTRACT

The combination of high-resolution multi-spectral satellite imagery and advanced COTS object-oriented image processing software provides for an automated terrain feature extraction and classification capability. This information, along with elevation data, infrared imagery, a vehicle mobility model and various meta-data (local weather reports, Zobler Soil map, etc...), is fed into automated path planning software to provide a stand-alone ability to generate rapidly updateable dynamic mobility maps for Manned or Unmanned Ground Vehicles (MGVs or UGVs). These polygon based mobility maps can reside on an individual platform or a tactical network. When new information is available, change files are generated and ingested into existing mobility maps based on user selected criteria. Bandwidth concerns are mitigated by the use of shape files for the representation of the data (e.g. each object in the scene is represented by a shape file and thus can be transmitted individually). User input (desired level of stealth, required time of arrival, etc…) determines the priority in which objects are tagged for updates. This technology was tested at Fort Knox, Kentucky October 11th – 15th 2004. Satellite imagery was acquired in a near-real-time fashion for the selected test site. Portions of the resulting geo-rectified image were compared with surveyed range locations to assess the accuracy of the approach. The derived UGV Path Plans were ingested into a Stryker UGV and the routes were autonomously traversed. This paper will detail the feasibility of this approach based of the results of this testing.

1. INTRODUCTION

When you think about robotic path planning what comes to mind? The Floyd-Warshall algorithm, A*, D*, Johnson's algorithm, etc... And when you think about autonomous vehicles, what comes to mind – Tank Automotive Research Development and Engineering Center (TARDEC) Robotic Systems, Army Research Lab's (ARL) XUV, Carnegie Mellon University's (CMU) Sandstorm, Defense Advanced Research Projects Agency's (DARPA) PerceptOR program? What do all these things have in common? For the algorithms to function and for the vehicles to navigate, they all need detailed information about the environment around them. And not just the local data readily available from the vehicles on board sensors, but detailed a priori data of the region the vehicle will traverse. Some of the most highly advanced Unmanned Ground Vehicles (UGVs) of our day depend on this to function.

> *"The key enabling technology behind the Red Team and SciAutonics II was a priori terrain mapping. Both teams acquired Digital Terrain Elevation Data (DTED) maps of the entire event course…"*
> *- Insider's View of the 2004 DARPA Grand Challenge*

So how do these systems get this vital information? Many use a combination of local sensor-suites on the vehicle and an a priori database of local terrain information. The local sensors generally acquire higher resolution data but in a much smaller region (10's of meters from the vehicle), whereas the a priori database tends towards lesser resolution but at a larger scope (10's of kilometers for a given region). Typically the map data (a priori database) is used for

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
25 MAR 2005	**Journal Article**	**15-01-2005 to 21-03-2005**

4. TITLE AND SUBTITLE **Remote Imagery for Unmanned Ground Vehicles (RIUGV)**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Philip Frederick; Robert Kania; Bernard Theisen; Derek Ward; Ursula Benz**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Lockheed Martin Missiles And Fire Control - Dallas,PO Box 650003 MS WT-52,Dallas,TX,75265**	8. PERFORMING ORGANIZATION REPORT NUMBER **; #14739**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000**	10. SPONSOR/MONITOR’S ACRONYM(S) **TARDEC**
	11. SPONSOR/MONITOR’S REPORT NUMBER(S) **#14739**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

submitted to SPIE Defense and Security Symposium

14. ABSTRACT

The combination of high-resolution multi-spectral satellite imagery and advanced COTS object-oriented image rocessing software provides for an automated terrain feature extraction and classification capability. This information, long with elevation data, infrared imagery, a vehicle mobility model and various meta-data (local weather reports Zobler Soil map, etc...), is fed into automated path planning software to provide a stand-alone ability to generate rapidly pdateable dynamic mobility maps for Manned or Unmanned Ground Vehicles (MGVs or UGVs). These polygon ased mobility maps can reside on an individual platform or a tactical network. When new information is available, change files are generated and ingested into existing mobility maps based on user selected criteria. Bandwidth concerns are mitigated by the use of shape files for the representation of the data (e.g. each object in the scene is represented by a shape file and thus can be transmitted individually). User input (desired level of stealth, required time of arrival, etc?) determines the priority in which objects are tagged for updates. This technology was tested at Fort Knox, Kentucky October 11th ? 15th 2004. Satellite imagery was acquired in a near-real-time fashion for the selected test site. Portions of the resulting geo-rectified image were compared with surveyed range locations to assess the accuracy of the approach. The derived UGV Path Plans were ingested into a Stryker UGV and the routes were autonomously traversed. This paper will detail the feasibility of this approach based of the results of this testing.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

determining the overall path, and the sensor data is used to correct for dynamic environment changes (fallen trees, large racks, other vehicles, etc..)

Where does this a prori information come from? The National-intelligence Geospatial Agency (NGA) is the DOD provider for geospatial information. They provide the elevation and imagery data that feed current automated robotic path planners. Current turnaround time on generating an elevation database or segmenting an image into features is on the order of months and is labor intensive. This required amount of time and manpower will not meet the needs of the future force.

"… the Army has insufficient capabilities to generate the Future Force common operating terrain and weather effects database …"
- Spatial Data Formats for Unmanned Military Vehicles

What if the feature extraction portion could be automated? This paper not only looks at the possible difficulties and benefits, but delves into what has already been done and highlights the results of recent field tests.

2. PROGRAM ORIGIN

Vehicle navigation has changed dramatically over the past 50 years. The 1950s gave way to the Inertial Navigation System (INS), providing vehicle operators with their heading and speed. In the 1960s the Navy Navigation Satellite System (NNSS), or Transit, became operational providing a two-dimensional (latitude, longitude) positioning using the Doppler shift of the signal. Follow on work provided three-dimensional (longitude, latitude, altitude) positioning in the 1970s. The 1980s lead way to the Global Positioning System (GPS) and differential GPS (DGPS). In the 1990s the Wide Area Augmentation System (WAAS) lead the way to Wide-Area DGPS (WADGPS) and the United States offers to make GPS standard positioning service (SPS) available to the international community.

Since the early 90s there has been research conducted at U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) and Army Research Labs (ARL) on semi-autonomous and autonomous vehicle navigation. One of these joint initiatives was the DEMO III program. In this program semi-autonomous navigation was demonstrated using scout-sized unmanned vehicles capable of basic off-road semi-autonomous operation during day or night. Poor weather, unpredicted terrain anomalies, and information overload in cluttered areas effected system performance. The Vetronics Technology Integration (VTI) program leveraged these Demo III technologies and integrated them on two STRYKER Infantry Carrier Vehicles (ICVs) to demonstrate military significant operations. The factors that effected semi-autonomous navigation in Demo III are mitigated in VTI by implementing a leader-follower approach. The first STRYKER vehicle is the Crew integration and Automation Testbed (CAT). This is a manned leader vehicle that lessens the computational requirements for semi-autonomous/autonomous navigation by allowing a manned vehicle to plot a safe course. The other STRYKER is the Robotic Follower (RF). This is an unmanned platform that follows paths laid out by the CAT, including those with significant spatial and temporal separations.

Both vehicles have the same sensor suite and could be interchanged in the leader follower roles. They are also both capable of individual semi-autonomous navigation utilizing Digital Topographic Elevation Database (DTED) data and known terrain features. However, this approach is limited to availability of known terrain features.

The goal of the RIUGV project is to provide terrain features in an automated near-real time fashion for areas where no previous terrain or leader route data exists. A number of government and Commercial-off-the-Shelf (COTS) software modules where combined to create this capability.

2.1 eCognition

The first version of eCognition was introduced to the worldwide market in autumn 2000. Over a period of only 4 years, eCognition has proved to be a quantum leap in the realm of digital remote sensing. It is now possible to handle complex classification problems, which require the consideration of local context information or other spatial data sets. eCognition is the world's only software for contextual classification of earth observation imagery.
Due to its unique capabilities eCognition is used for a wide range of applications such as: environmental and natural resources monitoring, forestry, agriculture, defense and intelligence, pipeline monitoring, urban mapping, natural hazard

detection, coastal/marine mapping, exploration & mining, and disaster management. All products feature the unique Object Oriented Image Analysis technology.

2.2 Wizard for Advanced Feature Extraction (WAFE)

Detailed land cover analysis of remote areas is necessary for many mission planning applications. This information can be derived from remote sensing imagery. Up until now image analysts have extracted the relevant features from this imagery in a time consuming manual process.

In 2002, Definiens Imaging performed their first feasibility study (WAFE I) to determine if features could be extracted from commercially available data in a highly automated fashion. The main focus was on using high resolution, optical spaceborne data, which was acquired by the two satellites – IKONOS and Quickbird. Based on the results of this study; it became evident that the cabibilty to automatically generate a mobility database would be of great benefit.

Under the WAFE II contract (2003 and 2004) Definiens Imaging started the development of eCognition WAFE, a customized version of eCognition enterprise. eCognition WAFE is designed to globally extract advanced features as input for a mobility database with minimum ground measurements. The software will interoperate with the routing systems for unmanned ground vehicles.

The architecture of eCognition WAFE follows the hierarchical & modular concept of cognition technology. Therefore, the concept supports continuous updating and refining of an initial mobility database using multi-source and multi-temporal information.

The initial mobility database relies on publicly available information, such as weather information, Zobler soil data, worldwide available spaceborne imagery, and a Digital Elevation Map (DEM). Thus, this mobility database can be generated anywhere in the world with similar accuracy.

WAFE II was finished in 2004 with the first prototype of eCognition WAFE. It uses IKONOS data for land cover analysis, a digital height model from SRTM data, Zobler soil type information from USGS and weather information from public METAR data. Using this commercially available remote sensing information the eCognition WAFE prototype automatically generates an initial mobility database. This mobility database is already accurate and detailed enough to seed the route planning of unmanned vehicles.

The WAFE prototype enables a continuous updating and refinement of this initial map. Additional information from LADAR can be used to get more detailed information on surface roughness. New Ikonos imagery can be used to see changes within the land cover or get information for cloudy regions from a prior data take. This capability, to integrate airborne LADAR data, was shown at an earlier test at Fort Dix.

During the WAFE II development period, a significant portion of work was dedicated to the interoperability of a fully automatic routing system. Future developments plan to extend the capability of eCognition WAFE to extract information from on-board sensors of the UGV and use this information to continuously refine and improve the mobility database with each measurement. Furthermore the applicability of eCognition WAFE to other areas in the world and during different vegetation periods will be increased.

2.3 Pathfinder

The Pathfinder route planning and arc-node network generation algorithms were developed under the Footprint to Pathfinder (F2P) project. This project was funded through the Urban Operations Focus Area Collaborative Team (UO FACT) and was a three-year effort that started in Fiscal Year 2002. F2P was started to support computer generated forces development and focused incorporation of its products into two emerging simulations: COMBATXXI and One Semi Autonomous Force (OneSAF) Objective System (OOS). Algorithms were developed for characterizing urban footprints, assessing structural damage (including rubble generation in urban terrain subjected to conventional weapons attack), ground vehicle mobility and determining routes for ground vehicles through the urban environment.

The problem of routing vehicles in an urban environment initially concentrated on solving the routing problem on the road network, and has gradually incorporated open areas such as parks and parking lots. The difficulty with of finding a path in space has led to the use of graph search methods to solve this problem. An arc-node network is used to mathematically represent the areas of navigation and the A* algorithm is used to find the "best" path through the network given starting and ending coordinates. Constraints can be imposed such as no go areas, restricting movement through an axis of advance, specifying intermediate waypoints that the vehicle must pass, specifying known obstacles that can limit or hinder vehicle movement, and the consideration of perceived threat locations.

A network generator was also developed to generate an arc-node network from terrain databases. Initially, compact terrain databases (CTDB) were used as a source. This was changed to the OOS Environment Runtime Component when the COMBATXXI development team switched to this format. For the RIUGV test, a network generator was developed to handle the shape file format. Because COMBATXXI was chosen as the demonstration platform to interface with the route planning and network generation algorithms, all code was written in Java.

2.4 Standard Mobility Modeling Suite (STNDMob)

The STNDMob was developed for the Army as a means to bring consistency of ground vehicle mobility modeling predictions to the model & simulation (M&S) community. However, because it is a derivation of the NATO Reference Mobility Model, the STNDMob brings consistency with the test and experimentation, acquisition, and battle command communities as well. Each module of the STNDMob suite is tailored to meet the special needs of each user, but are tied to the same core capability to predict the maximum terrain-limited-speed of a given ground vehicle. Since STNDMob is designed as an Application Programmer's Interface, it is fairly easy to integrate in other applications.

3. RESULTING PRODUCT

RIUGV integrated the capabilities of eCognition WAFE, Pathfinder, and the Standard Mobility Modeling Suite with an existing government-owned graphics user interface (Falcon View). Generation of the mobility map information (Fig. 1) was automatic and derived from the latest pass imagery of the IKONOS satellite on the test site (Fig. 2).

The Ecognition WAFE combination was passed the raw satellite imagery and generated a detailed object level shape file map from this and the other metadata previously discussed (soil maps, local weather information, etc). This map could then be used by the Automated Route Planner. An optimized route for user selected end points and interim way points was then generated, with the estimated speed made good and route traversal time for the route estimated by vehicle specific calls to the Standard Mobility Modeling Suite.

The output of the process consisted of a series of lat-long coordinates to be executed by the UGV, along with an estimate of maximum speed and traversal time for each portion of the route. The combined product's ability to accurately characterize the prospective route was the principal question examined during the live UGV testing..

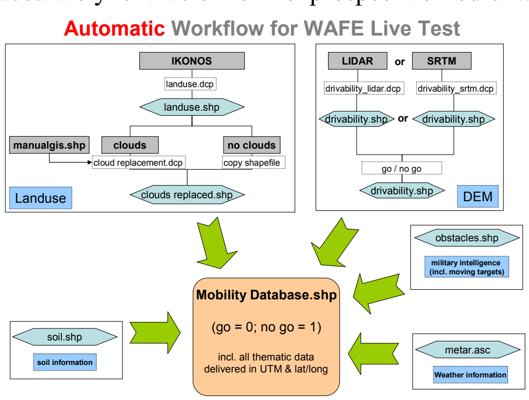


Figure 1: Workflow Process for UGV Live Test

Figure 2: Workflow Process for UGV Live Test

3.1 eCognition WAFE

Test preparations included the acquisition of pre-test IKONOS imagery of the test site and the generation of a mobility data base, as a fall back position in case of partial or full cloud cover during the test period.. Also Shuttle Radar Topography Mission (SRTM) data was acquired to get a high resolution digital terrain map to calculate terrain roughness and slope.

The IKONOS data take for the live test was requested within a 5 day time window before the actual planned run of the UGV. The actual test data take was successfully acquired by IKONOS with little cloud cover and was provided to Definiens Imaging through ftp by European Space Imaging within a 4 hour window. Using the customized software, eCognition WAFE, basic land cover polygons were fully automatically extracted. Each polygon was classified as: water body of various types, forest of various types and heights, smooth and rough low vegetation, road and trails of various types or man made targets. For all road polygons the centerlines were identified and provided as a line shape file. Elevation data was derived from the high resolution digital elevation model based on X-band SRTM data provided by German Aerospace Centre (DLR) to Definiens Imaging – the roughness of the terrain was included and also estimated by the software.

eCognition WAFE automatically created a vehicle specific mobility database from this data (Fig. 3). All object polygons in this database were tagged with the appropriate source image, land cover, terrain slope, weather information and USGS soil type data. The system demonstrated the ability to derive a high accuracy mobility map for the test area within 5 hours of the actual image take. Preliminary testing has also shown that the technology scales well over extremely large areas (i.e. full satellite image tiles of 100x100 Km), with total processing time being a function of image complexity. Several 'flavors' of the mobility map were generated to examine the location accuracy of the derived objects: one with just image provider rectification, one with correlated imagery improved rectification, and one with six additional ground rectification measurements.

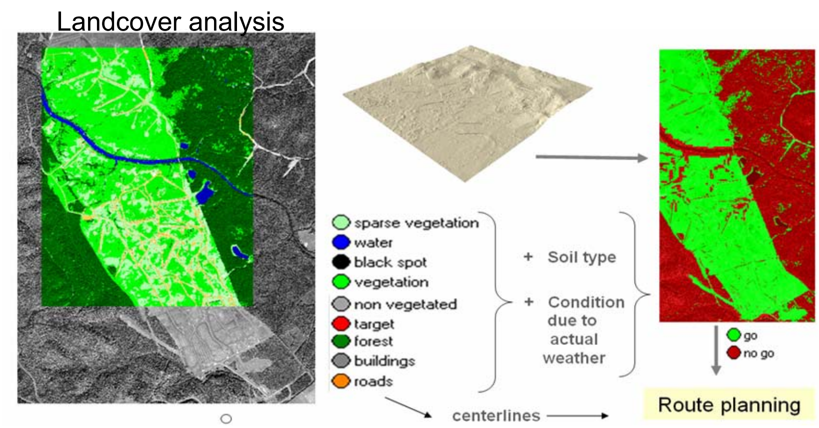


Figure 3: Fort Knox mobility database generation

Using 6 ground control points, the resulting shape file was re-georectified using ArcGIS. The object-based approach let it appear feasible that the rectification process can be provided with high accuracy with minimum amount of ground measurements. Next developments will focus on advanced and highly atomized registration to ensure the necessary geo-spatial accuracy.

Following the generation of the map file, the Falcon View GUI and Pathfinder were given two user selected routes for generation – one cross country (Fig. 4 & 5) and one road bound (Fig. 6). The lat/lon coordinates generated by the combined software suite for these routes were downloaded to a memory stick and loaded into the executive software of the UGV employed in the test environment.

Figure 4: Off-Road Course Images: Ground Shot, Panchromatic Satellite Image, Extracted Feature Map, Go/No-Go Map

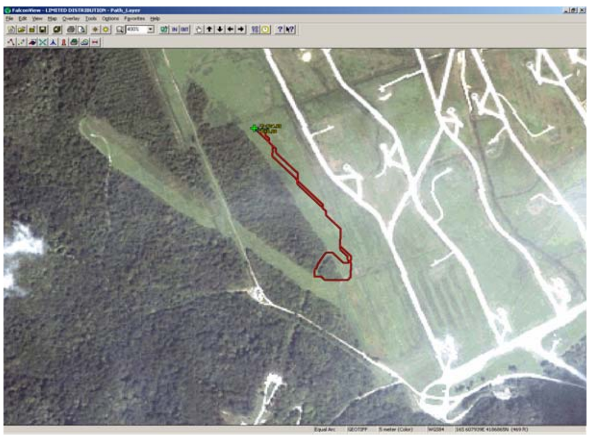


Figure 5: Generated off-road path displayed in Falconview

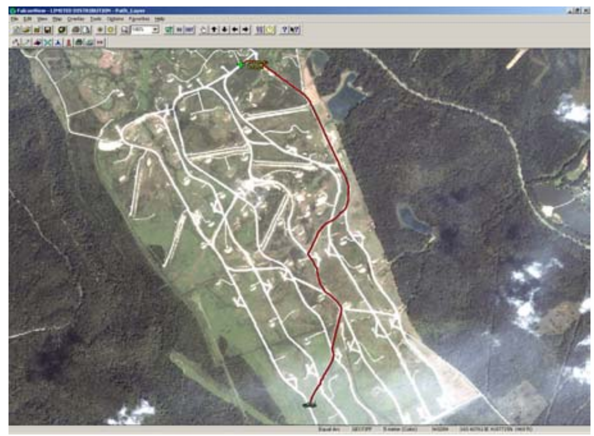


Figure 6: Generated road bound path displayed in Falconview

The Standard Mobility Modeling Suite also generated speed estimates and segment traversal times for each portion of the selected route. The exemplary routes illustrated in Figures 4&5 consisted of approximately 160 GPS coordinates with matching speeds and traversal times. Examination of the accuracy of these estimates was not an immediate test objective, but will likely be examined in 2005 testing.

Further tests on Fort Dix (Fig. 7) showed the advantage of the hierarchical and modular software architecture: If more detailed information is available as airborne LADAR data, the mobility data base can be successively refined without any changes in the methods for the initial data base creation and without multiple calculations.

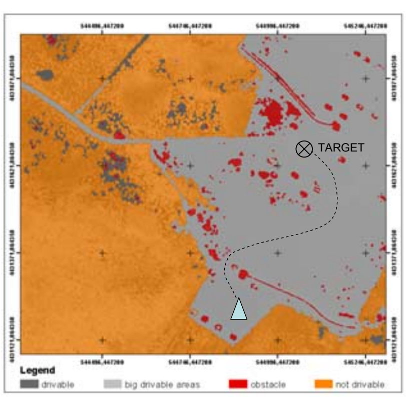
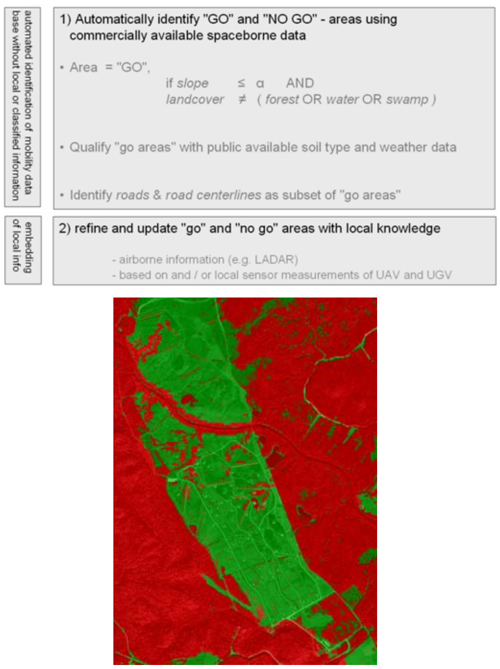


Figure 7: Drivability map of a Fort Dix range based off LADAR data

3.2 Pathfinder

Pathfinder finds a route for individual ground vehicles on an arc-node network. The arc-node network is a representation of the roads and traversable off-road areas. The network is generated using two sources: shape files and Digital Terrain Elevation Data (DTED) files. The shape files contain polygons representing the features on the terrain, e.g., roads, forested areas, rivers, buildings, open areas, etc. Associated with each polygon is data such as soil type needed to determine the speed of a vehicle traversing that polygon. In addition, the polygons are flagged as "go/no go" to allow/avoid routing the vehicle through the feature (Fig. 8). For example, a feature such as a road or open area would be flagged "go" while a building or a ditch would be flagged "no go". The DTED files contain elevation postings needed to determine slope, another factor for determining vehicle speed.



Layer	Attribute	Go	No
Land use	Forest		
	Vegetation		
	Sparse		
	Roads		
	Non vegetated		
	Water		
	Buildings		
	Concrete		
	Black Spot		
	Trench		
SRTM	Slope ≤ 35°		
	Slope > 35°		
Military intelligence	Obstacle		

Figure 8: Determination of go/no-go areas for RIUGV mobility Database

Currently, network generation involves generating the road network and the off-road areas separately and then merging the two networks into one. The road network is presently constructed manually using a simple graphical user interface. With the road polygons displayed on the screen, nodes are placed at intersections and along curves in the road to break the curves into a series of short linear segments. The nodes are then linked by the arcs. The off-road network is generated automatically.

A vehicle in an off-road area could possibly move in an infinite number of directions. This must be restricted in order to reduce the number of possible paths that may potentially be examined when searching for the optimal path. In addition there are an infinite number of locations that the vehicle may occupy. This must be reduced to a finite number of points and must be as small as possible without compromising the optimality of the path.

To achieve these goals, the off-road areas are subdivided into square girds. A node is placed in the center of each grid. Arcs link the node of a grid to the nodes of the grids that are physically adjacent to the given grid. Therefore, it is possible to go in eight directions (less if the grid is along the border of the terrain) from a node. The grid size was set to ten meters for each side. (This worked well for the Stryker UGV, but for a smaller UGV a smaller grid size should be considered.)

The merging of the road network with the off-road network was also an automated process. Transition points were set up along roadways where the road and off-road areas met to allow vehicles to move from one medium to the other.

The arc-node network is a directed graph where each arc a_{ij} from node i to node j has a real valued, non-negative cost c_{ij}. The problem is to find the shortest path from a source node s to a terminus node t by solving:

$$\text{Min} \quad \sum_{j}^{N}\sum_{i}^{N} C_{ij}X_{i}$$

$$\text{Subject to :} \quad \sum_{j}^{N} X_{ij} - \sum_{j}^{N} X_{ji} = S_i \forall i$$

$$\begin{aligned}
\text{Where :} \quad & N = \text{total number of nodes,} \\
& i, j = \text{nodes,} \\
& C_{ij} = \text{the cost of travel to node } j \text{ from node } i \ (\geq 0), \\
& X_{ij} = 1 \text{ if i and j are on the shortest path, 0 otherwise,} \\
& S_i = 1 \text{ if } i = \text{s}, -1 \text{ if } i = \text{t, 0 otherwise.}
\end{aligned}$$

Equation 1: Shortest path determination

The A* algorithm is commonly used to solve this problem in the context of finding the optimal path for ground vehicles, and this algorithm is implemented in Pathfinder. The cost of traversing an arc is adapted from COMBATXXI. It considers two factors, travel time and risk from perceived threats. Travel time is a function of speed and distance. Distance is obtained from the arc's length and speed is obtained from calling the Standard Mobility API. The risk is obtained from threat circles laid over the network. A threat circle is a circular area where a threat is perceived to exist. A weight from 1 to 100 is assigned to the threat circle where larger values are associated with higher risks for the vehicle traveling through the circle. The risk is zero outside the threat circle. The total arc cost is:

$$\begin{aligned}
& C_{ij} = (W_{travel} * T_{ij}) + (W_{risk} * R_{ij}) \\
& \quad 0 < W_{travel} \leq 1 \\
& \quad 0 \leq W_{risk} < 1 \\
& \quad W_{travel} + W_{risk} = 1 \\
& \quad T_{ij} = \text{travel time component (normalized)} \\
& \quad R_{ij} = \text{risk component (scale from 0 to 100)}
\end{aligned}$$

Equation 2: Arc cost determination

W_{travel} and W_{risk} are weights applied to, respectively, the travel and risk components of C_{ij}. They are used to determine how much each component contributes to the overall cost. For example, if a route is needed for a vehicle within an area where it is seen to be secure from any threat, travel time becomes the only factor to consider in the arc's total cost, so W_{travel} is set to 1 and W_{risk} is set to 0. If travel and risk contribute equally to the total cost, both W_{travel} and W_{risk} are set to 0.5.

It should be noted that this cost function is not "hard-wired" into the A* algorithm code. A cost function class was written and an instance of this class was passed to the A* code. If a different cost function is required, a separate cost function class can be written. It can then be instantiated and passed to the A* code. This allows a library of cost functions to be maintained and eliminates rewriting the A* code whenever a new cost function is introduced.

The capability exists to consider other constraints. Although these were not used during the RIUGV test, short descriptions of two additional constraints are presented here. The first constraint is the no-go area. It is a polygon that is laid over the network. If a situation arises where a vehicle is prohibited from entering a certain area (either for military or political reasons), a no go area polygon can be created to delineate that area. The route planning algorithm will not consider any arc wholly, or partially, located within the no-go area. The second constraint is the axis of advance. It is defined as "a line of advance assigned for purposes of control; often a road or a group of roads, or a designated series of locations, extending in the direction of the enemy." It is implemented as a polygon that encloses a series of arcs. Vehicle movement is restricted to only those arcs and nodes that lie within the polygon. The vehicle

enters the axis of advance through a designated node called the checkpoint node. This node is located inside the polygon and it is characterized by the fact that it has an arc linked to a node outside the polygon.
The checkpoint node becomes the first node that a vehicle visits inside the polygon. The vehicle exits the axis of advance through one or more designated exit nodes. An exit node, like a checkpoint node, is located inside the polygon and has an arc linked to a node outside the polygon. The exit node becomes the last node the vehicle visits before leaving the polygon. The purpose of the exit node is to force the route planning algorithm to search in the direction the vehicle is intended to move through the axis of advance.

Given these specifications, the route planning algorithm breaks the problem up. It first determines the least cost path from the source node to the checkpoint. Once in the axis of advance, the algorithm tries to find the least cost path from the checkpoint to the exit node, considering only those arcs and nodes within the polygon. The algorithm finally finds the least cost path from the exit node to the terminus. If multiple exit points are specified, the algorithm chooses the least cost alternative between routes from the checkpoint to each exit node and then on to the terminus.

3.3 Standard Mobility Modeling Suite

One module of STNDMob is used in conjunction with the Pathfinder algorithm to pre-process all possible maneuver routes in the selected area given typical terrain conditions. The STNDMob acted as a service to the Pathfinder algorithm to predict the maximum speed of the UGVgiven the terrain conditions provided by Pathfinder.

A second module, designed to execute faster, works with the real/near-real type navigation system to predict terrain-limited speeds due to dynamic changes in the environment. This module was written in the programming language C++, rather than Java as the other modules are written with, in order to obtain faster execution. This particular module, referred to as STNDMob-Lite, predicts a maximum speed of the UGV, but the speed is capped at the controlled speed of the UGV. Thus, at the fairly low speeds permitted for the experiment the model serves to provide the navigation system with go and no-go predicitons for all practial purposes (Fig 9).

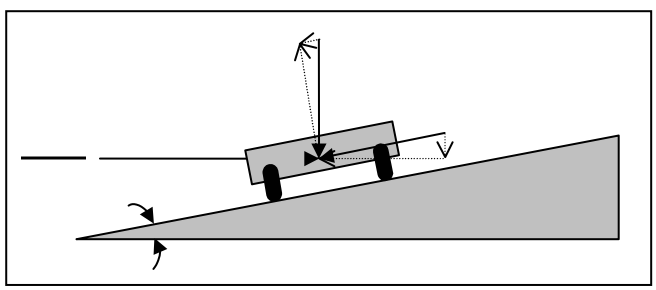


Figure 9: STNDMob GUI and mobility determination example

4. TEST RESULTS

RIUGV Engineering and Evaluation Tests (EETs) were conducted at Fort Knox October 11th – 15th as part of Vetronics Technology Integration (VTI) Operational Testing. Unmanned vehicle navigation tests were conducted on the 11th and site surveys were performed 12th – 15th. System performance was measured according to the following metrics.

- Positional accuracy of extracted features
- Accuracy of predicted soil and vegetation states
- Accuracy of predicted road centerlines
- Accurate classification of mobility impediments
- Feasibility of traversal of generated paths

4.1 Positional accuracy of extracted features

Feature accuracy was found to be a measure of position in the image, number of correlated images, and number and location of rectification points incorporated into the scene. Objects located in the geometric center of the image or the center of rectification, when incorporated, were more precisely positioned (~ 3.5 meters) than objects outside this region. When multiple images were leveraged in the production of the feature map, ground truth accuracy was found to increase to a similar degree (~3 m). However, the key to accurate positioning was the insertion of surveyed rectification points. Through the insertion of these surveyed points, object accuracy was resolved to sub-meter or near sub-meter levels (Fig. 10). The position and number of rectification points were understood to be important during the collection process and selected to produce the expected best results (Fig 11). No data was collected to conduct a study to determine the ideal number or position of these points.

On average, a non-rectified scene had accuracies between 5 – 10 meters while a rectified scene had accuracies between sub and 1.5 meters. A certain level of uncertainty was introduced to these measurements in the experimental procedure. Vehicle tasking did not allow for ground truth and rectification measurements to be taken with the vehicles GPS unit. This introduces potential drift between receiver estimates. Also, ground truth and rectification points were based off single GPS readings rather than an average of readings taken over an extended period of time.

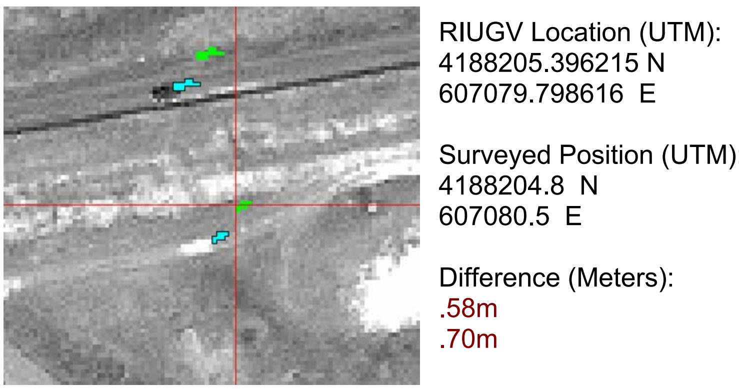


Figure 10: Survey vs RIUGV location of a HMWWV

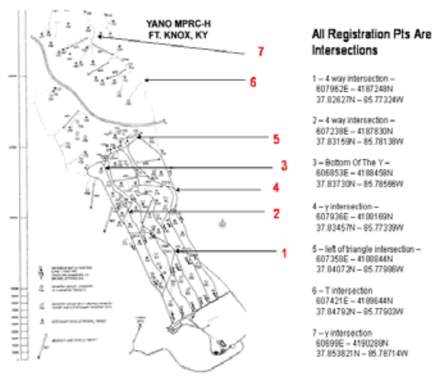


Figure 11: Ground Rectification Points

4.2 Accuracy of predicted soil and vegetation states

Vegetation classifications were measured against Digital Topographic Data (DTOP). RIUGV classifications were more refined than the data contained in the DTOP file. DTOP contained basic definitions of vegetation boarders while RIUGV extracted individual trees. The general vegetative border was the same for both sources (Fig 12) with accuracies as described in section 4.1. Soil state estimates were verified through visual verification. Future testing will include a detailed site survey including collection and analysis of soil and vegetation samples.

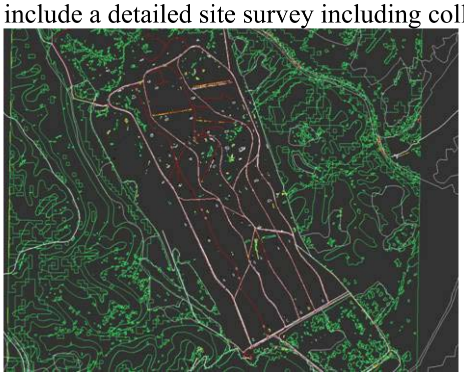


Figure 12: DTOP (White – roads and vegetation) vs. RIUGV (Green - vegetation and Red - roads) definition of roads and vegetation

4.3 Accuracy of predicted road centerlines

A fractal growth algorithm was used to find the center of road objects. A real world navigation test was performed on the road layer of the data with the VTI Crew integration and Automation Testbed (CAT) Stryker UGV to test the algorithms performance. Roads were extracted with two images correlated and rectification points incorporated. The RIUGV path (Fig. 6) was generated from two waypoints at the South East and North West corner of the road network. The generated path was compared with DTOP centerlines and human driven centerline data. DTOP data was considered the control for the experiment. Results indicated deviations in accuracy from less than a meter to 3 meters. On average, the RIUGV centerlines had a deviation from the DTOP centerlines of approximately a meter to a meter and a half. Deviation was less for human recorded centerline data, on the order of a meter or less. This can be attributed to RIUGV and Human data being developed/recorded specific to the STRYKER UGV traversing the terrain. The DTOP data was dated cache information (file generation date was 01/18/00, survey date is unknown) with the recording means unknown. Nevertheless, the DTOP data was considered the control for the experiment due to the low probability of detailed platform specific road centerline data being available during an operational experiment across foreign terrain.

The detection of road centerlines was not an optimized procedure. The inclusion of a smoothing algorithm will provide for a more consistent path. The system does not identify/classify intersections. Accounting for these situations will improve the accuracy of generated routes through these areas.

4.4 Accurate identification of mobility impediments

The vehicle mobility map was based off of a basic go/no-go definition file (Fig. 8). This file is a result of the mobility characteristics of the vehicle (from STNDMob) and terrain state (feature type, height, and weather conditions). A site survey confirmed that all recognizable mobility impediments were identified in the map. Recognizable mobility impediments were characterized by test engineers as those that the vehicle could not traverse based off of slope or type (e.g. body of water).

Two small areas' of the map were tagged as no-go and could not be quantified as such by engineers (fig 13). It is likely that difference in heat signature between terrain and surrounding vegetation or expected soil moisture content were the alarms that tagged these areas as not traversable.

Figure 13: No quantifiable no-go spots

4.5 Feasibility of traversal of generated paths

An on-road and off-road RIUGV path was generated and traversed by the CAT UGV (Fig. 5&6). These paths were selected to test particular attributes of the system (ability to produce a long accurate on-road path containing multiple turns and the ability to generate a viable off-road path even through covered terrain). However, these paths were also selected with vehicle and safety-driver health in mind (across areas with little or no elevation change). Highly demanding paths were also generated that contained multiple changes in elevation and other mobility impediments. These paths were surveyed by test engineers and deemed traversable by the STYKER UGV. However, a portion of one particular path would have presented an interesting mobility challenge for the UGV. The path generated required the UGV to traverse a drainage ditch at its flattest point (Fig 14). The ditch had a near 90 degree change in elevation at depths of 10-12 feet on either side of the selected path. The path selected was a gradual change in elevation, due to erosion of soil, that was determined to be traversable by a STRKYER. Given that the STNDMob mobility model used was one of a manned STRKYER platform, this was deemed a viable route.

Figure 14: Eroded path through the ditch

5. TEST COMMENTS AND FUTURE PLANS

The results from this field test have proven that near-real-time feature extraction from satellite imagery is a viable a prori data source for UGV path planning. Additional rectification work (e.g. number/location of rectification points for a given scene) needs to be conducted to provide the most accurate and efficient results. However, it is feasible to expect this work to be conducted in the near future and for those results to further verify this approach. For operations in known terrain, where ground measurement data already exists (most of the US and Europe), this information can be ingested from known sources without the need for survey data. Future work towards automatic rectification during UGV/MGV traversal could eliminate this need altogether.

Future plans for RIUGV include work that will increase the accuracy of road centerline estimations, classify intersections and develop UGV behaviors for these situations, and integrate near real-time UGV sensor data (i.e. LADAR, color or IR cameras). These additional capabilities were selected as the most promising to meet short term VTI goals. Additional future efforts could include incorporation of UAV sensor data and automated UGV based scene rectification.

6. REFERENCES

1. D.Poole, A.Mackworth, R.Goebel, *Computational Intelligence - A logical Approach*, Oxford University, New York, 1998.
2. S. Pace, G. Frost, I. Lachow, D. Frelinger, D. Fossum, D. wassem, M. Pinto, *The Global Positoning System - Assessing National Policies*, RAND, New York, 1995.
3. E. Sutton, S. Rosengren, *Combined GPS and Vision System Navigation*, University of Florida, Shalimar, 2004
4. A. King, *Inertial Navigation - Forty Years of Evolution*, GEC Review, Vol. 13, No. 3, 1998
5. P.Frederick, R.Kania, D.Ward, N.Goerger, *Spatial Data Formats for Unmanned Military Vehicles,* NDIA Intelligent Vehicle Systems Symposium, 2004
6. R.Kania, P.Frederick, J.Jaczkowski, *Insiders View of the DARPA Grand Challenge*, NDIA Intelligent Vehicle Systems Symposium, 2004
7. DOD Dictionary of Military Terms - **http://www.dtic.mil/doctrine/jel/doddict/**

*frederip@tacom.army.mil; phone (586) 574-6840; fax (586) 574-8684